DEEP: A Distributed Energy Efficient Routing Protocol for Internet of Nano-Things

Saoucene Mahfoudh[1], Areej Omar Balghusoon[2]
School of Engineering, Computing and Design,
Dar Al-Hekma University, Jeddah 34801, Saudi Arabia[1]
Faculty of Computing and Information Technology,
King Abdul Aziz University, Jeddah 21589, Saudi Arabia[2]

***Abstract*—Nanotechnology offers transformative capabilities across healthcare, environmental monitoring, and industrial automation. When integrated with modern communication technologies, Wireless Nano Sensor Networks (WNSNs) form the Internet of Nano Things (IoNT), interconnecting nanoscale devices with conventional networks. Despite its potential, efficient routing in IoNT remains challenging due to severe energy constraints, limited processing, and high propagation losses in the terahertz (THz) band. This paper proposes the Distributed Energy-Efficient Protocol (DEEP), a lightweight routing scheme designed for IoNT-based WNSNs. DEEP balances simplicity, connectivity, and sustainability through adaptive retransmission control and a hybrid energy model combining environmental energy harvesting with wireless power transfer. Performance evaluation using the Nano-Sim module of the NS-3 simulator demonstrates that DEEP significantly extends network lifetime, reduces overall energy consumption, and maintains scalability and robust delivery performance with minimal communication overhead.**

***Keywords*—Routing protocol; Internet of Nano Things; nanosensor; energy efficiency; energy harvesting; terahertz communication**

I. Introduction

The rapid expansion of ubiquitous connectivity among diverse devices has accelerated the realization of the Internet of Nano Things (IoNT), an emerging paradigm that extends interconnectivity to the nanoscale and enables innovative applications across multiple domains. At the core of this paradigm lies the Wireless Nanosensor Network (WNSN), which enables communication among nanoscale devices through electromagnetic or molecular signaling mechanisms, forming the foundational infrastructure of IoNT. Defined as the interconnection of nanoscale sensors, devices, and nanomachines with traditional networks and the Internet, IoNT promises transformative impacts in healthcare, agriculture, smart cities, industrial monitoring, and other areas [1], [2], [3].

In healthcare, IoNT-enabled nanosensors embedded within the human body can monitor biomarkers in real time and deliver targeted therapies, supporting minimally invasive and highly precise treatments [4], [5]. In agriculture and environmental monitoring, nanoscale devices enable high-resolution measurements of soil composition, humidity, and pollutant levels, promoting sustainable and efficient resource management [6]. When integrated with advanced communication systems and machine learning algorithms, IoNT and WNSNs can further support autonomous decision-making and anomaly detection in complex environments such as industrial automation and smart infrastructures [7].

Despite these benefits, the extreme miniaturization of nanosensors imposes significant constraints that challenge the design and deployment of WNSNs [8]:

- Nano-antennas: Graphene-based THz antennas provide high bandwidth but suffer severe attenuation and noise, limiting communication to micro-/millimeter distances.
- Nano-processors: Extremely limited computational capabilities restrict data processing to small data units.
- Nano-batteries: Very limited energy storage, often irreplaceable, imposes strict energy constraints.

To mitigate energy limitations, energy harvesting has emerged as a promising solution, enabling nanosensors to partially replenish energy from blood flow, molecular vibrations, or body movement. However, harvested energy is intermittent and insufficient for continuous communication, introducing additional constraints on routing and network management. Maintaining network operation under fluctuating energy availability, while minimizing communication overhead, remains a key challenge [9], [10].

Motivated by these challenges, this paper introduces the Distributed Energy-Efficient Protocol (DEEP), an energy-aware routing solution designed for IoNT-based WNSNs. DEEP seeks to optimize network performance while minimizing energy dissipation, particularly in in-body applications where communication and energy constraints are most pronounced. It reduces redundant transmissions through an adaptive retransmission mechanism and integrates a hybrid energy model that combines variable-rate harvesting with wireless power transfer (WPT) to support sustainable nanosensor operation. Furthermore, DEEP is developed with consideration of realistic nanoscale communication and device constraints, including THz propagation effects and the inherent limitations of nanosensor hardware.

The main contributions of this paper are summarized as follows:

- Novel distributed hop-count routing protocol: DEEP employs a lightweight, deterministic mechanism suitable for nanoscale devices with extremely limited memory and computational capacity.

- Adaptive retransmission strategy: Reduces redundant transmissions and extends network lifetime under fluctuating energy availability.
- Hybrid energy model: Combines realistic energy harvesting for sustainable network operation.
- Comprehensive simulation with biologically plausible channel models: Demonstrates improved packet delivery, lower overhead, and enhanced energy efficiency compared to standard baselines.
- Comprehensive simulation with biologically plausible channel models: Demonstrates improved packet delivery, lower overhead, and enhanced energy efficiency compared to standard baselines.

The remainder of the paper is organized as follows. Section II presents IoNT architectures, WNSN characteristics, and existing routing protocols. Section III describes the proposed DEEP protocol, including the energy model and network architecture. Section IV details the simulation setup and performance evaluation. Finally, Section V concludes the paper.

II. Literature Review

The design of an efficient routing protocol in conjunction with nanodevice specification necessitates a comprehensive understanding of the core hardware components. Furthermore, it involves a detailed investigation of network architecture, terahertz-band wireless communication, and the selected energy supply strategy to effectively meet the intended application objectives [11].

A. IoNT Architecture

The architecture of an Internet of Nano Things (IoNT) network depends on the application domain but generally consists of four fundamental components: nanonodes, nanocontrollers, nano-microinterface (gateway) devices, and an Internet gateway [12], [13]. Fig. 1 illustrates the IoNT architecture in a plant monitoring system.

- A nanonode is the smallest and simplest nanodevice, acting as a nanosensor or nanoactuator with limited resources and transmission range, capable of basic tasks such as sensing, actuating, processing, and storage.
- A nanocontroller or nanorouter is a more resourceful and capable device than a nanonode, responsible for coordinating nanonodes, processing their collected data, and forward it through the nano-microinterface.
- Nano-microinterface (Gateway) acting as a bridge between the nanoscale network and external systems, this hybrid device uses terahertz communication with nanonodes and conventional protocols for external communication. It aggregates data from nanocontrollers and facilitates bidirectional interaction between nanosystems and the Internet.
- Internet Gateway provides remote control and monitoring of the IoNT system via the Internet, enabling data collection from nanonetworks and access by external applications.

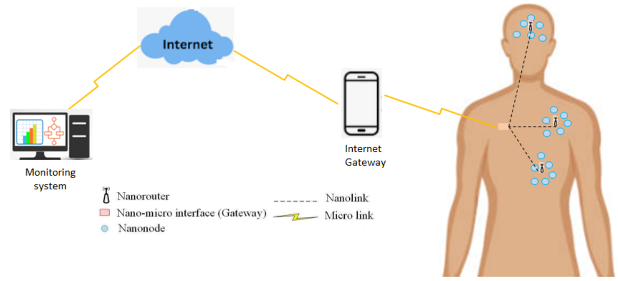


Fig. 1. IoNT architecture in healthcare system.

B. Principle Characteristics of a Nanodevice

In WNSNs, a nanodevice is the fundamental unit, either functioning as a nanonode (nanosensor/nanoactuator) or nanocontroller. With dimensions on the nanometer scale, these devices enable applications such as environmental monitoring, medical diagnostics, and biochemical detection. A typical nanodevice integrates multiple hardware components, including sensing/actuation, processing, communication, storage, and power units [14], [15], [16], [17].

Due to their small size, nanodevices face severe constraints in processing, communication, and energy, which are critical for network sustainability [18]. To address these limitations, network design must account for two critical aspects: terahertz (THz) wireless communication and energy supply systems. THz wireless communication using graphene-based nanoantennas (0.1–10 THz) offers extremely high data rates and wide bandwidth suitable for nanoscale networks [19]. However, propagation is limited by molecular absorption, noise, and frequency-selective path loss, confining effective transmission to a few millimeters in air and even less in biological media.

Energy supply is equally crucial. The tiny form factor of nanodevices limits onboard energy storage, affecting network lifetime and performance. Two main approaches have been explored: nanobatteries and energy harvesting. While nanoscale batteries provide temporary energy storage, they are impractical to recharge or replace in real network deployment. Energy harvesting, using nanogenerators that convert mechanical, vibrational, thermal, or electromagnetic energy into electricity, offers a more sustainable solution. Techniques such as piezoelectric and thermoelectric nanogenerators, as well as wireless power transfer (WPT), can prolong device operation and enable continuous network functionality. Despite advances, developing efficient, scalable energy solutions remains a key challenge for practical IoNT and WNSN deployments. Incorporating energy-harvesting mechanisms introduces additional complexity, as the available energy in nanodevices becomes highly dynamic and time-varying. Consequently, communication strategies in WNSNs must be designed to accommodate these fluctuations by jointly considering both energy consumption and harvesting rates. Ensuring continuous connectivity therefore requires adaptive protocols that operate efficiently under variable energy availability and maintain stable network performance despite the intermittent and unpredictable nature of harvested energy.

C. Related Works: Routing Protocols for IoNT

Many routing protocols have been proposed for the IoNT. The survey in [20] provides a comprehensive review and classification of these routing protocols.

In study [11], [21], and [22], cluster-based routing schemes are presented. Piro et al. in study [11] introduced a hierarchical framework that integrates intra-body nanonetworks with macro-scale healthcare systems to enable bidirectional communication between nanodevices and external devices. They proposed two energy-aware routing schemes: an optimal protocol that maximizes cluster energy through complex selection processes, and a simpler greedy protocol that selects nanosensors with the highest residual energy. A MAC-layer handshake mechanism was employed to identify active sensors and their energy levels. Simulation results using Nano-Sim showed that both approaches outperform conventional flooding techniques.

In study [21], nanosensors are organized into clusters to maintain efficient network connectivity. Each cluster consists of a coordinator, members, and relay nodes, with coordinator selection based on residual energy and packet forwarding ratio. Communication takes place through intra-cluster and inter-cluster phases, utilizing single- or multi-hop transmission depending on energy efficiency. Although this method outperforms random forwarding, it does not account for the energy harvesting characteristics of nanodevices. This work was later extended in study [22] by incorporating a detailed channel model and an integrated energy framework that considers both energy harvesting and consumption. The proposed layered nanonetwork architecture forms clusters within each layer, with cluster heads elected based on residual energy. Data transmission is organized into periodic phases, combining intra-cluster and inter-cluster communication managed by the nanocontroller through prioritized scheduling. Simulation results using Nano-Sim demonstrate that the proposed scheme achieves higher energy efficiency and lower outage probability compared to the baseline method in study [23].

In [24], two routing protocols for IoNT-based healthcare applications—naïve and destructive retrieval—were proposed. Both rely on a hop-count propagation phase initiated by the gateway to establish routing paths. In the naïve scheme, nanosensors forward packets toward the gateway based on hop-count comparisons, while the destructive retrieval algorithm improves efficiency by resetting the forwarding node's hop count to infinity, thereby preventing redundant transmissions. Although simulations in NS-3 confirm that the destructive retrieval approach reduces message overhead compared to the naïve method, the model assumes static nodes with unlimited energy and lacks consideration of energy constraints, mobility, and practical deployment overhead. The study in [25] presents a hierarchical Body Area Network (BAN) architecture modeled on a human hand, where an external gateway is positioned on the dorsum, a nanocontroller is implanted beneath the skin, and nanosensors circulate with the bloodstream. Both the nanocontroller and nanosensors are powered through energy harvesting, utilizing piezoelectric nanowires and a rechargeable nanocapacitor, with wireless power transfer (WPT) from an external ultrasound source. In the proposed routing mechanism, nanosensors remain in sleep mode until sufficient energy is accumulated, waking periodically upon entering the ultrasound region to exchange data with the nanocontroller. Analytical results indicate that communication occurs approximately every 52 minutes; however, the approach lacks simulation validation and relies on a single nanocontroller, which may lead to processing overhead.

In [26], the authors propose a dynamic multihop routing model that integrates electromagnetic nanocommunication properties with hemodynamic behavior. They introduce a theoretical framework based on reinforcement learning, formulated as a four-dimensional Markov Decision Process (MDP) that includes nanonode velocity, event priority, energy consumption, and energy-harvesting capacity. Performance analysis under varying parameters, such as nanonode density, vessel diameter, and flow speed, shows that the proposed multihop approach significantly improves the nanonetwork's effective coverage area.

Table I summarizes the main IoNT routing protocols, highlighting their approach, energy model, channel assumptions, simulation environment, and key limitations.

III. Distributed Energy Efficient Routing Protocol

This section outlines the development process of the proposed routing protocol. We begin by presenting the underlying design principles, then describe the adopted network architecture and the key assumptions. Next, we outline the energy supply mechanisms and summarize the energy models employed. Finally, we explain the protocol phases, its operational behavior, and the conceptual inspiration guiding the design.

A. Principles of the Proposed Routing Protocol

The objective of DEEP is to enhance network performance while minimizing energy consumption and extending the operational lifetime of nanoscale networks. DEEP is a distributed hop-count–based routing protocol in which each nanodevice independently makes forwarding decisions using only local information. The protocol is tailored for IoNT architectures, where communication typically involves two segments: (i) nanosensor–nanocontroller, and (ii) nanocontroller–gateway.

Pierobon et al., in [23], demonstrated that data transmission and reception dominate energy dissipation in nanoscale communication, whereas processing costs are negligible. Consequently, reducing unnecessary packet retransmissions is essential for avoiding premature node depletion and improving overall network performance. DEEP addresses this by minimizing the number of nodes participating in packet forwarding, thereby lowering both communication overhead and energy dissipation.

To achieve these goals, the protocol design adheres to the following principles:

- Support for multiple energy supply systems: DEEP incorporates two energy mechanisms—wireless power transfer (WPT) and environmental energy harvesting—resulting in two protocol variants: DEEP-WPT and DEEP-Harvesting.

TABLE I. COMPARISON OF IoNT ROUTING PROTOCOLS

Protocol	Approach	Energy Model	Channel Model	Simulation	Limitations
Piro et al. [11]	Cluster-based	Residual energy	Simplified	Nano-Sim	Complex selection; limited THz realism
Afsana et al. [21], [22]	Multi-layer clustering	Residual energy + energy framework	Partial THz	Nano-Sim	No dynamic energy harvesting; no adaptive retransmissions
Buther et al. [24]	Hop-count (naïve & destructive)	Unlimited energy	Deterministic	NS-3	Unrealistic assumptions; no mobility/energy constraints
Canovas et al. [25]	Energy-harvesting aware	Harvesting + WPT	Partial THz	Analytical	Single nanocontroller; limited simulation
Garcia et al. [26]	Reinforcement learning	Harvesting-aware	Electromagnetic + hemodynamic	Simulation	Complex; high computational overhead

- Minimal resource usage: Each nanodevice stores only one routing record and performs simple comparison-based operations, aligning with the strict memory and processing constraints of nanoscale hardware.
- Energy-aware next-hop selection: The protocol uses a minimum-hop strategy to limit the number of forwarding nodes, thereby reducing total energy consumed per delivery path.
- Reduction of redundant transmissions: An adaptive retransmission mechanism limits unnecessary rebroadcasts, mitigating the high overhead associated with flooding-based approaches.

To achieve these goals, we first describe the adopted network architecture and the underlying assumptions in the next subsection, which serve as the basis for the DEEP protocol design.

B. DEEP Network Architecture and Assumptions

The proposed routing protocol is designed for in-body medical applications, where reliable nanoscale communication is essential for continuous physiological monitoring. The adopted architecture follows a hierarchical IoNT structure, which is widely considered suitable for in-body nanonetworks. In this architecture, the nanoscale network communicates with an external device (e.g., a smartphone), which subsequently interfaces with a healthcare provider through the Internet, forming a complete IoNT system. The wireless interface between the WNSN and the external device can be achieved using conventional technologies such as Bluetooth.

Fig. 1 illustrates the adopted IoNT architecture. Nanosensors, nanocontrollers, and the gateway are deployed in a 3D in-body environment. Nanosensors are assumed to exhibit micro-mobility, reflecting the small-scale displacements induced by physiological processes such as tissue deformation, and cellular vibrations. This mobility is characterized by slow, short-range, and does not break the topology, which do not lead to large topological changes but may slightly affect link availability and communication reliability. Such a micro-mobility model is suitable for organ- or tissue-level monitoring scenarios in which nanosensors are embedded in specific anatomical regions—such as the skin, heart, lung, or kidney—to detect abnormalities or biomarkers.

Nanocontrollers and the gateway, by contrast, are considered quasi-static because they are implanted in fixed anatomical locations to facilitate data aggregation and onward communication. Each nanodevice is assigned a unique identifier and is equipped with a graphene-based nano-antenna to support electromagnetic nanoscale communication. All devices employ Time Spread On-Off Keying (TS-OOK) modulation, a pulse-based communication scheme shown to be energy-efficient and suitable for THz-band communication [27].

Nanosensors periodically sense physiological parameters and forward their data to nearby nanocontrollers, which then relay the aggregated information toward the gateway. The gateway subsequently delivers the collected data to an external computing system, enabling remote monitoring and analysis by healthcare providers.

C. The Energy Supply Systems

The DEEP protocol is evaluated under two distinct nanoscale energy supply mechanisms. In both cases, each nanodevice is equipped with a piezoelectric nanogenerator [28] capable of harvesting energy either from an external wireless power source or from ambient physiological activity.

1) Wireless Power Transfer (WPT): In the first energy model, nanodevices harvest energy through wireless power transfer, where an external ultrasound emitter radiates waves that are converted into electrical energy. Under WPT, the harvested energy rate is assumed to be constant, enabling nanodevices to remain continuously active unless the external source is disabled.

This continuous activity does not imply that the network is overloaded. DEEP mitigates excessive resource usage by minimizing packet retransmissions, thereby reducing collisions and lowering energy expenditure. Under WPT, nanodevices operate in one of two states:

- Transmission: Actively forwarding or generating data packets.
- Reception: Receiving either new or duplicate packets.

2) Harvesting from environment: In the second energy model, nanodevices harvest energy from local physiological vibrations. Human tissues exhibit diverse vibration sources—such as muscle movements, blood flow, cardiac activity, and respiration—each characterized by different frequency ranges. As a result, the energy harvesting rate becomes time-varying and dependent on factors such as the nanodevice's location, blood pressure, and proximity to cardiovascular structures.

Under this mode, a nanodevice transitions between two operational states:

- Active: The device can transmit or receive packets.
- Sleep: Triggered when the stored energy drops below a threshold. In this state, the radio is disabled to allow faster energy accumulation.

Although energy harvesting occurs in both states, the harvesting rate is significantly higher during sleep mode due to reduced power consumption.

3) Energy models: The energy harvesting and consumption models adopted in this work must be compatible with TS-OOK pulse-based modulation. Both models are derived from the nanoscale framework proposed by Jornet et al. [28].

a) Energy harvesting model: Human physiological activity produces vibrations across a broad spectrum, from approximately 1 Hz (e.g., foot tapping) to over 300 Hz (e.g., running) [29]. These variations translate into highly dynamic harvesting rates.

The harvesting rate λ_e is computed as a function of the current energy in nanocapacitor E_{cap} and the increase in the energy of the capacitor ΔE as presented in the following formula.

$$\lambda_e(E_{cap}, \Delta E) = \left(\frac{n_{cycle}}{t_{cycle}}\right) \cdot \frac{\Delta E}{n_{cycle}(E_{cap} + \Delta E) - n_{cycle}(E_{cap})} \quad (1)$$

where, the n_{cycle} is the number of compressed-release cycles of nanowires in piezoelectric generator and t_{cycle} is the time between consecutive cycles.

b) Energy consumption model: Nanodevices consume energy during transmission and reception operations. Sleep mode is assumed to incur negligible power consumption. This study accounts for:

- energy consumed when receiving data as final destination.
- energy consumed when receiving data as an intermediate node.

Overhearing and processing energy are excluded.

Transmission energy denoted $E_{packet-tx}$ and reception energy denoted $E_{packet-rx}$ per packet are calculated as :

$$E_{\text{packet-tx}} = E_{\text{pulse-tx}} * W * N_{\text{bits}} \quad (2)$$

$$E_{\text{packet-rx}} = E_{\text{pulse-rx}} * W * N_{\text{bits}} \quad (3)$$

where, N_{bits} is the packet size and W is the probability of transmitting a pulse (“1”). Following [28], $W = 0.5$ to reflect a balanced symbol distribution.

Finally, since protocol behavior depends on the underlying energy system, two DEEP variants—DEEP-WPT and DEEP-Harvesting—are developed to account for these differences.

D. Description of DEEP Protocol

DEEP’s goal is to build an end-to-end path (from any nanosensor to the gateway) while minimizing redundant retransmissions and ensuring reliable data delivery through a lightweight and deterministic forwarding mechanism. The nanonetwork operates across two segments:

- Nanosensor-to-nanocontroller communication: Data generated by nanosensors is forwarded hop-by-hop until it reaches the nearest nanocontroller. Hops in this case are nanosensors.
- Nanocontroller-to-gateway communication: Aggregated data is forwarded hop-by-hop to the gateway. Hops in this case are nanocontrollers.

Finally, the gateway forwards this data to the external computer through the Internet gateway. The present work focuses solely on the nanoscale communication domain, where the external side will adopt the existing protocols that fit the application.

DEEP operates in two main phases for both DEEP-WPT and DEEP-Harvesting namely, *topology discovery phase* and *data transmission phase*. The topology discovery process is identical across both variants, while data transmission behavior differs due to the energy supply mechanisms.

1) Topology discovery phase: The goal of this phase is to establish routing paths from nanosensors to nanocontrollers and from nanocontrollers to the gateway using a control message called the Topology Discovery (TD) packet. This phase is triggered by the destination which can be:

- The gateway to establish the Nanocontroller–Gateway Path: The gateway initiates the process by broadcasting a TD packet with a hop-count value set to 1. Each nanocontroller processes the packet according to Algorithm 1.
- The nanocontroller to establish the Nanosensor–Nanocontroller Path: Each nanocontroller broadcasts TD packets to nearby nanosensors with hop count initialized to 1. Nanosensors handle the packet using the same processing logic described in Algorithm 1.

When a nanodevice receives a TD packet, it processes it according to the logic illustrated in Algorithm 1. If this is the first time the nanodevice receives the TD packet (lines 1–7 of Algorithm 1), it performs the following actions:

- Updates its hop count field using the hop count carried in the TD packet, representing the number of hops required to reach the TD source (gateway or nanocontroller).
- Updates its destination address field with the source address contained in the TD packet.
- Updates its next-hop address field using the neighbor address attached to the TD packet.
- Increments the hop count value in the TD packet by one.

Algorithm 1 Nanodevice TD Reception Process.

```
1: if first reception then
2:     hop count Nanodevice ← hop count TD
3:     destination address Nanodevice ← source TD
4:     next hop address Nanodevice ← neighbor address TD
5:     hop count TD ← hop count TD + 1
6:     neighbor address TD ← Nanodevice address
7:     Forward TD
8: else
9:     if hop count Nanodevice > hop count TD then
10:        hop count Nanodevice ← hop count TD
11:        destination address Nanodevice ← source TD
12:        next hop address Nanodevice ← neighbor address TD
13:        hop count TD ← hop count TD + 1
14:        neighbor address TD ← Nanodevice address
15:        Forward TD
16:    else
17:        Discard
18:    end if
19: end if
```

- Replaces the neighbor address in the TD packet with its own address, allowing downstream nanodevices to identify their next hop.
- Forwards the updated TD packet to neighboring nodes.

If the nanodevice has already received a TD packet for the same destination (lines 9–15 of Algorithm 1), it compares the hop count stored locally with the hop count included in the newly received TD packet. If the new hop count is lower, the device updates its stored information using the same steps described above, ensuring that only the shortest-hop path is retained. Otherwise, the TD packet is discarded to prevent unnecessary retransmissions.

This process takes place recursively: nanocontrollers execute it when receiving TD packets from the gateway, and nanosensors execute it when receiving TD packets from nanocontrollers. By the end of the topology discovery phase, every nanodevice (nanosensor or nanocontroller) stores one compact routing record, containing the next-hop address. This enables DEEP to construct deterministic paths toward the gateway or nanocontrollers based on minimum hop count, ensuring efficient data forwarding with minimal overhead.

2) Data transmission phase: The data transmission phase begins after the completion of the topology discovery process. During this phase, each nanodevice forwards packets using only the local routing information stored in its routing record. As the energy supply differs between the two proposed variants, the operation of this phase is divided into DEEP-WPT and DEEP-Harvesting.

a) DEEP-WPT: In the WPT-based configuration, data transmission follows a simple and deterministic forwarding process. Each nanosensor periodically senses physiological parameters, generates a data packet, and forwards it to its designated next-hop nanodevice. Packets are forwarded hop by hop until they reach the assigned nanocontroller. The nanocontroller then forwards the aggregated data toward the gateway using its own next-hop entry, after which the gateway delivers the data to the external computing unit. Because all devices continuously receive energy from the external WPT source, they remain active at all times. Thus, the end-to-end path computed during the topology discovery phase remains valid throughout the data transmission period, eliminating redundant broadcasts and substantially reducing network overhead.

b) DEEP-harvesting: In the harvesting-based configuration, the same next-hop forwarding strategy is employed; however, the behavior of nanodevices is influenced by the intermittency of locally harvested energy. Since nanodevices may harvest energy from sources such as blood flow, heartbeat, or mechanical vibrations, the available energy varies significantly over time. When a nanodevice's residual energy drops below a predefined threshold, it must switch its radio off and enter a sleep state to replenish energy. During this period, the device cannot transmit or receive data packets.

As a result, if the sleeping device is the designated next hop on a computed path, data transmission will fail and the packet will be lost.

To mitigate this issue, DEEP-Harvesting introduces a lightweight control mechanism based on a Negative Acknowledgment (NACK) packet. When a nanodevice receives a data packet but lacks sufficient energy to forward it, it immediately sends a NACK to the previous hop before entering the sleep state. Upon receiving a NACK, the sender initiates a single-round controlled flooding of the data packet. Each nanodevice that receives this flooded copy forwards it according to its own next-hop record. To reduce unnecessary transmissions, nanosensors forward only those packets that are destined for their corresponding nanocontroller and discard packets addressed to other nanocontrollers. This selective relaying strategy confines the flooding area and prevents excessive energy consumption.

Algorithm 2 describes the packet reception behavior and NACK handling mechanism of the DEEP-Harvesting variant.

Algorithm 2 Nanodevice Reception Process for Data and NACK Packet

```
if Active nanodevice then
    if energy level ≥ threshold then
        Packet Type ?
        Case1: Data packet
        Forward data packet
        Case2: NACK packet
        Flood data packet with the same ID of NACK packet
        Case3: Flooded Data packet
        if nanocontroller then
            Forward data packet
        else
            if nanosensor && destination data packet
            == destination address in the record then
                Forward data packet
            else
                Discard
            end if
        end if
    else
        if energy level < threshold then
            if data packet: then
                Send NACK packet
            end if
            Sleep
        end if
    end if
end if
```

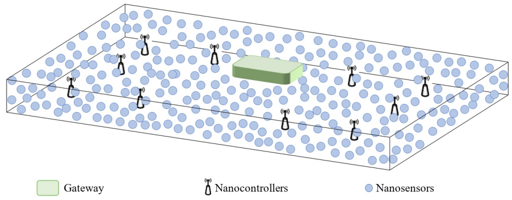


Fig. 2. Deployment area with 10 nanocontrollers for DEEP-WPT.

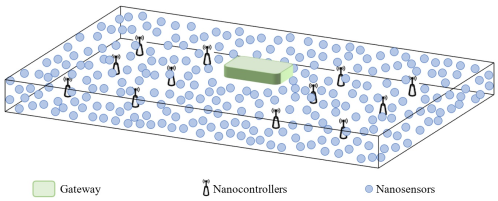


Fig. 3. Deployment area with 12 nanocontrollers for DEEP-harvesting.

TABLE II. SIMULATION PARAMETERS' VALUES

Parameters	The value
System parameters	
Results	Average of 10 simulation runs
Simulation duration	100 s
Number of gateways	1
Number of nanocontrollers:	
DEEP-WPT	10
DEEP-Harvesting	12
Number of nanosensors	250, 500, 750, 1000
Area size	0.03 × 0.09 × 0.001 m^3
PHY details	
$E_{Pulse-tx}$	1 pj
$E_{Pulse-rx}$	0.1 pj
Pulse duration	100 fs
Pulse Interarrival Time (The gap between two pulses in time)	10 ps
Transmission range of gateway	0.02 mm
Transmission range of nanocontrollers	0.02-0.01 mm
Transmission range of nanosensors	0.01 mm
Message Processing Unit	
Data Packet size:	256 bits

IV. Simulation and Performance Evaluation

All simulations are performed using Nano-Sim, a widely-used nanoscale network simulator for in-body IoNT scenarios. Each scenario is executed over 10 independent runs, and results are averaged to ensure statistical reliability.

A. General Simulation Parameters

Fig. 2 and Fig. 3, represent the simulated network in DEEP-WPT and DEEP-Harvesting, respectively. The network deployment as a whole is intended to approximate monitoring a small area inside human tissue or on organ surface. The gateway is located at the center of the area while nanocontrollers are distributed uniformly. However, nanosensors are scattered randomly in the network area. Nanodevices are assumed to be full charge in the beginning.

The nanosensors sense the ambient environment and produces data packets periodically. These packets are routed to the nearest nanocontroller then to the gateway. The transmission range was chosen based on Nano-Sim module, 0.01 mm for nanosensors and 0.02 mm for the gateway. To ensure that nanocontrollers can communicate with nanosensors and the gateway, it is sufficient to have two different transmission ranges either 0.01 or 0.02 mm. Table II presents the values of the simulation parameters that are common to all simulation's experiments.

B. General Evaluation Criteria

The main goal for DEEP protocol is to deliver the collected data while maximizing the network performance and minimizing the overhead and energy consumption. The evaluation criteria used to evaluate the protocol performance are:

- Number of received packets: Number of received packets by the gateway and by the nanocontrollers.
- Packet loss:

$$Packet\ loss = number\ of\ sent\ packets - number\ of\ received\ packets$$

- The network overhead: The number of control packets (TD and NACK) sent and received and the number of duplicated data packets in the network due to data flooding.
- Energy efficiency: Two ways to measure the energy efficiency based on the adopted energy supply system are used. In DEEP-WPT, the energy efficiency is measured based on the number of packets sent and received. Thus, we evaluate it implicitly with the overhead criteria. However, in DEEP-Harvesting, the energy efficiency is measured using Jornet energy model [28] described in the subsection 2 Eq. (2) and (3). Thus, we can calculate the total energy consumed in the network.
- Number of entering sleep state: Used only in DEEP-Harvesting. It indicates how many times nanodevices enter the sleep state due to energy depletion. This helps us to evaluate how the protocol put a load on nanodevices.

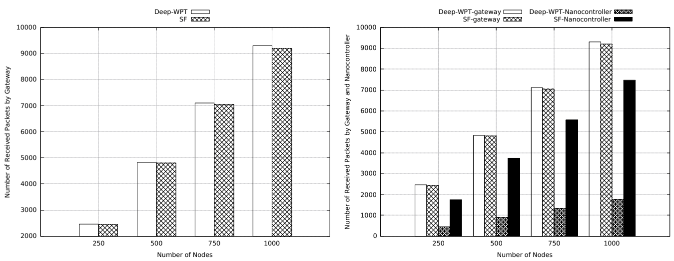
C. Comparative Performance Analysis

Due to the limited availability of IoNT routing protocols implemented in Nano-Sim, this study compares DEEP against Selective Flooding (SF) and Random Forwarding (RF), which are standard, reproducible baselines [30]:

- Random Forwarding (RF): Packets are forwarded to randomly selected neighbors; simple and low-overhead but prone to packet loss and duplication.
- Selective Flooding (SF): is an enhanced flooding algorithm for WNSN in which packets are broadcast to all neighbors with minimal redundancy control (only for the first reception).

Preliminary experiments show that SF consistently outperforms RF in terms of packet delivery ratio; therefore, SF is used as the primary baseline for detailed performance evaluation. We ran the SF protocol under the two different energy supplies: WPT to compare it with DEEP-WPT and harvesting from environment to compare it with DEEP-Harvesting.

1) Performance evaluation of DEEP-WPT: The results and discussions of the comparison between DEEP-WPT and SF protocol are presented in the following.



(a) (b)

Fig. 4. The number of received packets in WPT system: (a) By the gateway. (b) By the gateway and one nanocontroller.

a) Number of received packets: Fig. 4a presents the total number of packets received by the gateway using the DEEP-WPT and SF protocols. The results show that the number of received packets increases as the number of nanodevices grows, indicating that the protocol scales effectively with network size. Furthermore, DEEP-WPT consistently outperforms the SF protocol by delivering a higher number of packets to the gateway.

Fig. 4b illustrates the total number of packets received at the gateway as well as the average number received by a single nanocontroller. The results show that the DEEP protocol substantially reduces network overhead. Although DEEP delivers more packets to the gateway, the number of packets processed by each nanocontroller remains significantly lower compared to the SF protocol. For instance, with 1000 nanosensors, DEEP reduces the overhead on the nanocontroller by 77%. This improvement is attributed to the fact that SF relies on extensive packet flooding, which generates excessive retransmissions and rapidly consumes network resources, whereas DEEP transmits data hop-by-hop without unnecessary retransmissions.

Given the dense nature of WNSNs, DEEP is well suited for such environments. The performance results clearly demonstrate that our protocol offers better performance in terms of the number of packets successfully delivered.

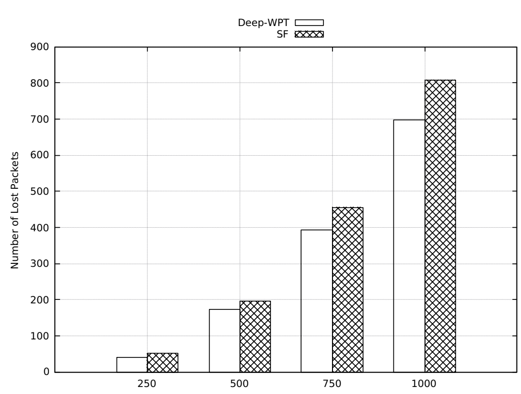
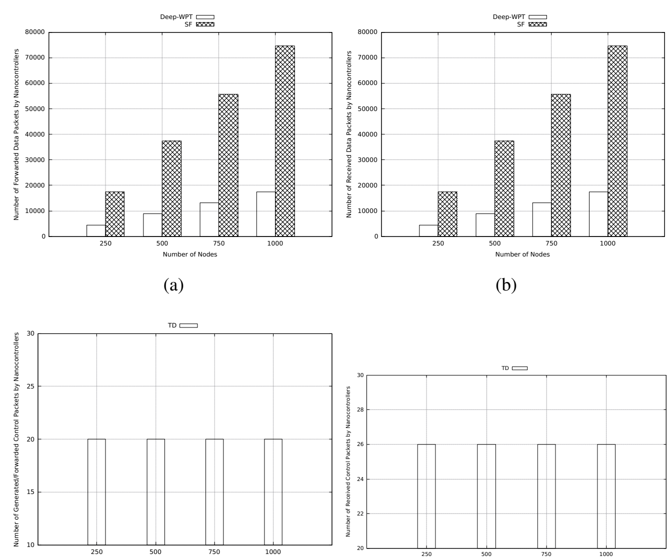


Fig. 5. The number of lost packets in WPT system.

b) Packet loss: Fig. 5 shows the number of packets lost as the number of nodes in the network increases. Packet loss in this scenario is mainly due to collisions between concurrent transmissions, as the use of a WPT energy supply system ensures that no node suffers from energy depletion. The results indicate that the DEEP protocol significantly reduces packet loss. For instance, when the network contains 250 nodes, DEEP decreases packet loss by 21.5% compared to SF. This improvement is attributed to the reduced communication overhead introduced by DEEP, which in turn lowers the number of simultaneous retransmissions.

c) The network overhead and energy efficiency: At nanocontroller level Fig. 6a shows the number of data packets sent by nanocontrollers while Fig. 6b shows the number of data packets received. Generally, as the number of nanodevices increases, the number of data packets sent and received by the nanocontrollers increases. However, DEEP substantial reduces the number of packets exchanged compared to SF protocol. This reduction reaches 77% when we have 1000 nanosensors in the network.

Furthermore, the number of control packets transmitted and received by nanocontrollers, illustrated in Fig. 6c and Fig. 6d, remains constant and does not depend on the number of nanosensors in the network, as the number of nanocontrollers is fixed. This quantity is negligible compared to the volume of data packets forwarded across the network. Consequently, we can conclude that the overall protocol overhead—including both retransmitted data packets and control packets (TD)—is minimal relative to the network overhead observed when using the SF protocol.



(a) (b)

(c) (d)

Fig. 6. The number of sent and received data and control packets by nanocontrollers in WPT system: (a) Sent data packets. (b) Received data packets. (c) Sent DEEP control packets. (d) Received DEEP control packets.

d) At nanosensor level: Fig. 7c and Fig. 7d depict the control packets sent and received by nanosensors, respectively. The number of control packets received and sent increases with the number of nodes on the network. To conclude, we observe that the overhead of DEEP protocol taking into account control packets and retransmitted packets remains very small compared to the number of packets sent and received using SF protocol which reaches millions of packets.

These results demonstrate that DEEP is an effective routing protocol for IoNT, providing sustained network connectivity while minimizing network overhead.

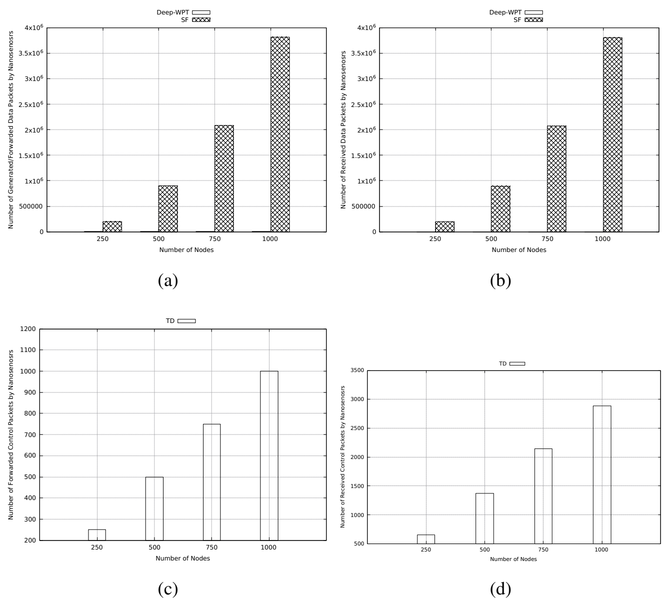


Fig. 7. The number of sent and received data and control packets by nanosensors in WPT system: (a) Sent data packets. (b) Received Data packets. (c) Sent DEEP Control packets. (d) Received DEEP control packets.

2) Performance Evaluation of DEEP-Harvesting: NanoSim does not natively support energy harvesting from the environment. Therefore, prior to presenting the results, we introduce additional simulation parameters in Table III, which are necessary to simulate DEEP-Harvesting.

TABLE III. THE PARAMETERS' VALUES FOR SIMULATING DEEP-HARVESTING

Parameter/Description	The value
Energy capacity: The energy level at the nanocapacitor Nanocontroller Nanosensor	 1600 pj 800 pj
w **weight code:** The probability to transmitting a symbol “1” instead of being silent “0”	0.5
Threshold: The minimum energy level that makes node entering the sleep state, which is equal to the energy required to transmit and receive one data packet	149.8 pj
Message generation probability:	0.2

a) Number of received packets: Fig. 8a shows the total number of packets received at the gateway using the DEEP-Harvesting and SF protocols. As illustrated, the number of received packets increases with the number of nanosensors up to 750 nodes, after which it decreases when the network includes 1000 nodes. This behavior is expected: as the number of nanosensors increases, more packets are generated, leading to higher energy consumption. Consequently, many nodes deplete their available energy and transition into a sleep state, resulting in packet losses within the network.

Despite this, DEEP consistently outperforms the SF protocol across all network sizes. For instance, with 1000 nanosensors, the gateway receives 134.12% more packets using DEEP compared to SF. This improvement stems from the limitations of the SF protocol, which relies on a flooding-based strategy that rapidly drains the energy of nanodevices and overwhelms the network with excessive retransmissions. As a result, nodes frequently exhaust their energy and enter repeated sleep cycles, preventing continuous network operation.

In contrast, DEEP significantly limits unnecessary retransmissions by establishing a dedicated path between the source and destination and minimizing flooding, thereby offering superior performance and more sustainable network operation.

Fig. 8b presents the number of packets received at the gateway, along with the average number of packets processed by the nanocontroller. When comparing DEEP with the SF protocol, DEEP reduces the processing overhead at the nanocontroller by approximately 60%, while still delivering a greater number of packets to the gateway.

These results clearly demonstrate that, under energy-constrained conditions, DEEP achieves superior performance compared to the SF protocol, particularly in terms of the number of data packets successfully delivered to the gateway.

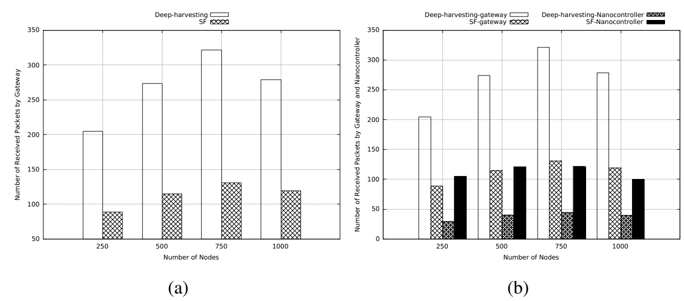


Fig. 8. The number of received packets in harvesting from environment system: (a) By the gateway. (b) By the gateway and one nanocontroller.

b) Packet loss: Because the number of packets generated in the DEEP and SF protocols is not identical, we present the percentage of lost packets—as shown in Fig. 9—rather than the absolute number of lost packets. The figure shows that the packet loss percentage increases as the number of nodes grows, which is expected given the corresponding rise in generated traffic. Nevertheless, DEEP consistently achieves a lower packet loss percentage compared to the SF protocol, demonstrating its ability to better preserve network reliability under increasing load.

c) The network overhead at nanocontroller level: Fig. 10a and Fig. 10b represent the number of sent and received data packets by nanocontrollers, respectively. In Fig. 10a, the increase in the forwarded packets with DEEP protocol is coming from the continuous operation of nanocontrollers that adopt DEEP. However, SF protocol exhausts the energy of nanocontrollers which enforces them to go to the sleep state many times rendering them inoperative. In SF, the energy

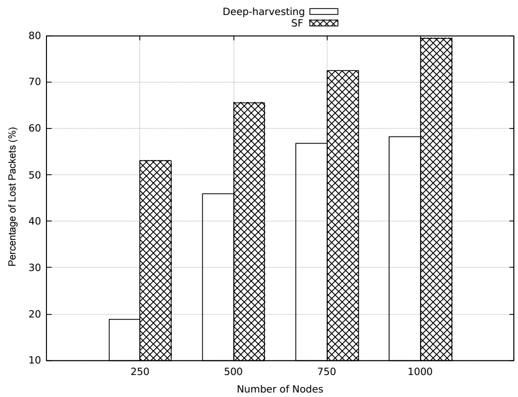


Fig. 9. The percentage of lost packets in harvesting from environment system.

of the nanocontrollers is dissipated in sending and receiving (as shown in Fig. 10b) duplicated packets which reduces the number of packets forwarded to the gateway.

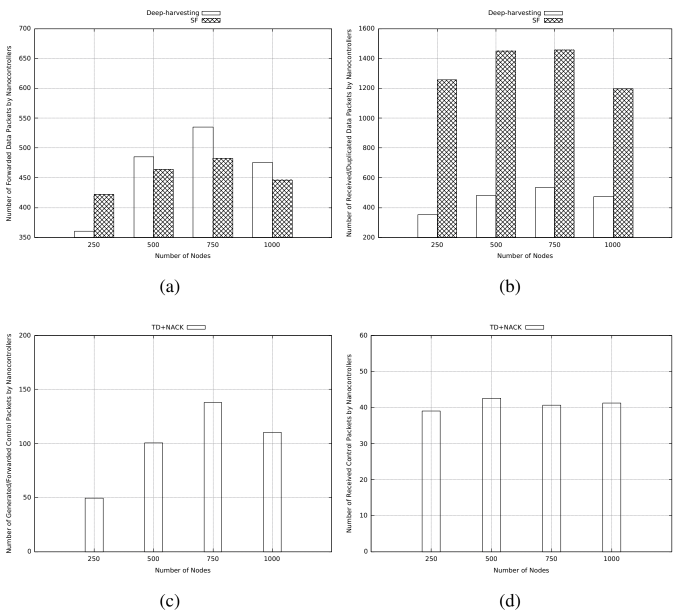


Fig. 10. The number of sent and received data and control packets by nanocontrollers in harvesting from environment system: (a) Data packets sent. (b) Received data packets. (c) DEEP control packets sent. (d) Received DEEP control packets.

Fig. 10c and Fig. 10d illustrate the number of sent and received control (TD and NACK) packets by nanocontrollers, respectively. Through these two figures, we can see that the overhead added by our protocol remains very small compared to number of messages duplicated in SF protocol. For example, for 500 nodes, the number of received control packets represents less than 4% of the number of duplicated packets in SF protocol.

d) The network overhead at nanosensor level: Fig. 11a provides the results of all the sent data packets (the generated and forwarded) by nanosensors for both protocols. The number of sent packets increases when the number of nodes increases. We observe that the number of packets generated and forwarded in DEEP protocol is 30% smaller than SF with 1000 nanosensors even so the number of packets received by the gateway is higher with DEEP.

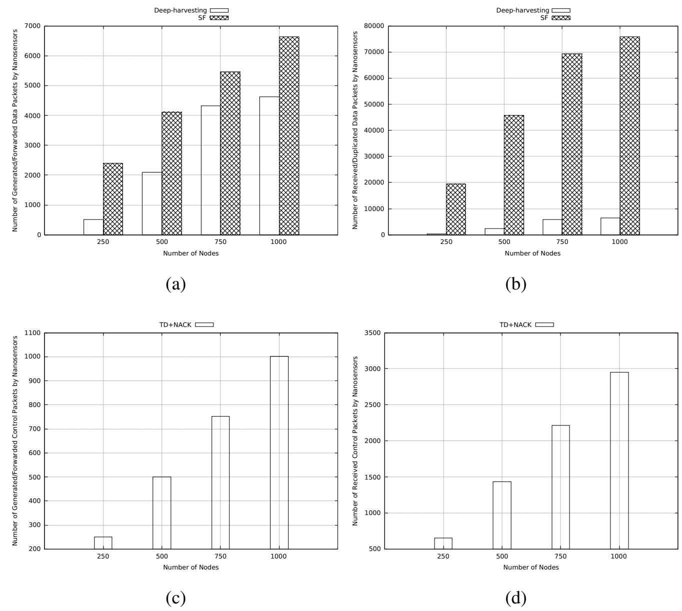


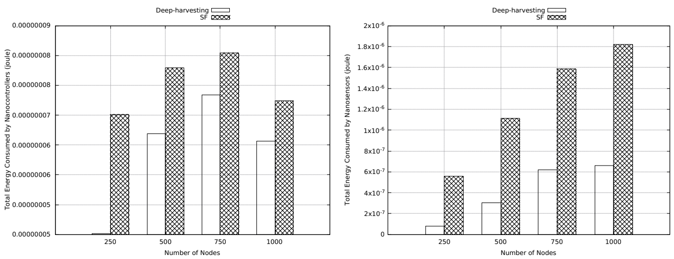
Fig. 11. The number of sent and received data and control packets by nanosensors in harvesting from environment system: (a) Data packets sent. (b) Received data packets. (c) DEEP control packets sent. (d) Received DEEP control packets. packets.

In the other hand, Fig. 11b depicts the number of received data packets by nanosensors including the duplicated data packets. We observe, from this figure, that DEEP reduces significantly the number of packets duplicated in the network. This reduction reaches 91% when the number of nanosensors is 1000 in the network.

Fig. 11c and Fig. 11d show the number of sent and received control packets by nanosensors, respectively. We can note that as the number of nodes in the network increases, the number of control packets received and sent increases. However, the overhead of DEEP protocol taking into account control packets and retransmitted packets remains very small compared to the number of duplicated packets using SF protocol.

Hence, SF exhausts the nanosensors' resources by unnecessary data packet retransmissions that reduces the network performance. However, DEEP reduces the retransmissions overhead at the network leading to best network performance under limited resources and difficult circumstance. That makes DEEP an energy aware routing protocol for IoNT, providing best network performance that balances between the routed data and the energy requirement.

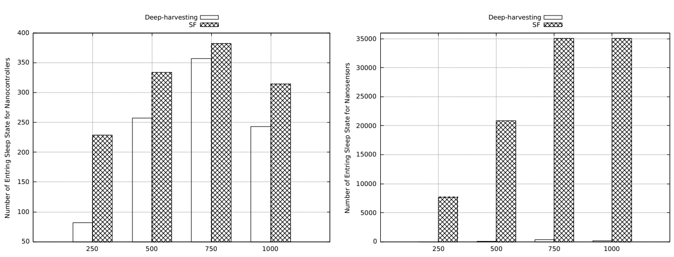
3) Energy efficiency: Fig. 12a presents the energy consumed by nanocontrollers under the DEEP and SF protocols. As shown, and consistent with the number of generated packets, the energy consumption fluctuates as the network size increases. Notably, nanocontrollers in DEEP consume less energy while transmitting both control and a higher volume of data packets, whereas the SF protocol requires more energy to transmit data packets alone.



(a) (b)

Fig. 12. The energy consumed by nanodevices in harvesting from environment system: (a) Nanocontrollers. (b) Nanosensors.

A similar trend is observed in Fig. 12b, which shows that nanosensors also consume significantly less energy when using DEEP. For instance, with 1000 nodes, DEEP reduces nanosensor energy consumption by 63.62% compared to the SF protocol. Importantly, this reduced energy expenditure is achieved while delivering a larger number of data packets to the gateway. Thus, DEEP enables both nanocontrollers and nanosensors to deliver more data with substantially lower energy consumption—an essential characteristic for any efficient routing protocol in energy-constrained nanonetworks.



(a) (b)

Fig. 13. Number of entering sleep state for nanodevices in harvesting from environment system: (a) Nanocontrollers. (b) Nanosensors.

- Number of entering sleep state: Fig. 13a and Fig. 13b illustrate the number of times nanocontrollers and nanosensors enter the sleep state, respectively. These results provide insight into how each routing protocol affects the depletion of harvested energy within the network. Across all device types, the number of nodes entering sleep under the DEEP protocol remains significantly lower than under the SF protocol. This behavior is expected, as SF relies on a flooding strategy that rapidly drains node energy, causing frequent transitions to the sleep state. In contrast, DEEP minimizes unnecessary flooding by leveraging the established routing paths generated during the topology discovery phase. Consequently, DEEP demonstrates its ability to sustain continuous network operation while maintaining performance levels that outperform SF in terms of energy preservation and operational stability.

Table IV summarizes the key differences between the two energy models in the proposed DEEP protocol: DEEP-WPT, which relies on wireless power transfer for predictable energy availability, and DEEP-Harvesting, which utilizes environmental energy sources with variable availability, highlighting their respective advantages, limitations, and suitable application scenarios.

TABLE IV. KEY DIFFERENCES BETWEEN DEEP-WPT AND DEEP-HARVESTING

Feature	DEEP-WPT	DEEP-Harvesting
Energy Source	Wireless Power Transfer (WPT)	Energy harvested from the environment (vibrations, biochemical reactions, EM energy)
Energy Availability	Continuous and predictable as long as the nanosensor is within WPT range	Intermittent and variable; depends on environmental conditions
Routing Stability	High stability due to reliable power availability	Moderate stability; depends on harvesting rate and stored charge
Node Density Influence	Less sensitive to density because energy is supplied externally	Highly dependent on density; more nodes allow more balanced harvesting
Best Use Cases	Fixed medical implants, body-area WNSNs, structured deployments	In-body nanosensing, environmental nanosensing, fluid or dynamic environments
Limitations	Requires dedicated power-transmitting infrastructure; limited WPT range	Energy levels fluctuate, leading to unpredictable forwarding behavior

V. CONCLUSIONS

This paper presented DEEP, a Distributed Energy-Efficient routing Protocol designed to improve reliability, reduce communication overhead, and minimize energy consumption in Internet of Nano Things (IoNT) environments. DEEP employs a hop-count–based routing strategy to establish efficient paths from nanosensors to nanocontrollers and ultimately to the gateway, ensuring reliable data delivery in in-body nanoscale networks. The protocol operates through two main phases: a topology discovery phase that identifies the shortest communication paths, and a data transmission phase that forwards packets along these optimized routes. To address the heterogeneous energy supply characteristics of nanodevices, two variants were developed: DEEP-WPT, which leverages wireless power transfer, and DEEP-Harvesting, which integrates ambient energy harvesting.

The protocol was implemented and evaluated using the Nano-Sim module within an in-body THz communication environment. Simulation results show that DEEP reduces redundant broadcast transmissions and lowers overall energy consumption. As network density increases, DEEP consistently outperforms selective flooding, achieving fewer retransmissions, higher energy efficiency, and sustained network operability. These findings demonstrate that DEEP is both scalable and well-suited for dense IoNT deployments.

Future work will focus on integrating nanosensor mobility models and extending the protocol to support more complex nanoscale architectures and cross-layer optimization.

ACKNOWLEDGMENT

This research was funded by the Vice President for Graduate Studies, Research and Business (GRB) at Dar Al-Hekma University, Jeddah, under grant no. (RFC/23-24/05). The authors, therefore, acknowledge with thanks GRB for technical and financial support.

DECLARATION ON GENERATIVE AI

During the preparation of this manuscript, the authors used GPT-5 for the purposes of proofreading. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

REFERENCES

[1] V. Padmavathy, M. B. Sakthiivanitha, V. Poornima, and R. Maruthi, "A comprehensive overview of internet of nanothings and its applications," *EAI Endorsed Transactions on Internet of Things*, vol. 10, Oct. 2024.

[2] A. Rana, D. Gautam, P. Kumar, K. Kumar, Vasilakos, A. Kumar Das, and V. Bhat K, "A comprehensive review of machine learning applications for internet of nano things: challenges and future directions," *Artificial Intelligence Review*, vol. 58, no. 7, 2025. [Online]. Available: https://doi.org/10.1007/s10462-025-11211-z

[3] E. Omanovic-Miklicanin, M. Maksimovic, and V. Vujovic, "The future of healthcare: Nanomedicine and internet of nano things," *Folia Medica Facultatis Medicinae Universitatis Saraeviensis*, vol. 50, 2015.

[4] M. Asghari and R. Asorey-Cacheda, "Local pulse wave velocity assessment by flow-guided nanosensor networks for early diagnosing and localization of atherosclerosis," *IEEE Sensors Journal*, vol. 25, no. 18, pp. 35 490–35 504, 2025.

[5] A. Boualem, H. Fouchal, M. Ayaida, and H. Kholidy, "Diagnosis of infectious diseases using nano sensors network in nanofluids," *BioNanoScience*, vol. 15, 2025. [Online]. Available: https://doi.org/10.1007/s12668-025-01972-w

[6] L. Jaiswal, A. Limayem, and S. Shankar, "Polysaccharide-based nanomaterials," in *Food, medical, and environmental applications of nanomaterials*. Elsevier, 2022, pp. 95–111.

[7] N. Hari, S. Radhakrishnan, and A. J. Nair, "Nanosensors as potential multisensor systems to ensure safe and quality food," in *Biotechnological approaches in food adulterants*. CRC press, 2020, pp. 204–238.

[8] A. Bamuqabel and S. Mahfoudh, "Deployment challenges in electromagnetic wireless nanosensor networks," *Sensors*, vol. 25, no. 23, 2025.

[9] S. Canovas-Carrasco, A.-J. Garcia-Sanchez, and J. Garcia-Haro, "On the nature of energy-feasible wireless nanosensor networks," *Sensors*, vol. 18, no. 5, p. 1356, 2018.

[10] S. R. Neupane, "Routing in resource constrained sensor nanonetworks," *Master of Science Thesis*, p. 74, 2014.

[11] G. Piro, G. Boggia, and L. A. Grieco, "On the design of an energy-harvesting protocol stack for body area nano-networks," *Nano Communication Networks*, vol. 6, no. 2, pp. 74–84, 2015.

[12] A. Alabdulatif, N. N. Thilakarathne, Z. K. Lawal, K. E. Fahim, and R. Y. Zakari, "Internet of nano-things (iont): A comprehensive review from architecture to security and privacy challenges," *Sensors*, vol. 23, no. 5, 2023.

[13] I. F. Akyildiz and J. M. Jornet, "The internet of nano-things," *IEEE Wireless Communications*, vol. 17, no. 6, pp. 58–63, 2010.

[14] I. F. Akyildiz, F. Brunetti, and C. Blázquez, "Nanonetworks: A new communication paradigm," *Computer Networks*, vol. 52, no. 12, pp. 2260–2279, 2008.

[15] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks*, vol. 1, no. 1, pp. 3–19, 2010.

[16] J. M. Jornet and I. F. Akyildiz, "The internet of multimedia nano-things in the terahertz band," in *European Wireless 2012; 18th European Wireless Conference 2012*. VDE, 2012, pp. 1–8.

[17] A. Nayyar, V. Puri, and D.-N. Le, "Internet of nano things (iont): Next evolutionary step in nanotechnology," *Nanosci. Nanotechnol*, vol. 7, no. 1, pp. 4–8, 2017.

[18] S. Canovas-Carrasco, A.-J. Garcia-Sanchez, F. Garcia-Sanchez, and J. Garcia-Haro, "Conceptual design of a nano-networking device," *Sensors*, vol. 16, no. 12, p. 2104, 2016.

[19] A. Ali, M. Aazam, M. M. Al Dabel, F. Ali, A. K. Bashir, S. El-Sappagh, and A. Al-Fuqaha, "Novel data fusion scheme for enhanced user experiences in terahertz-enabled iont," *IEEE Consumer Electronics Magazine*, vol. 14, no. 2, pp. 90–102, 2025.

[20] A. O. Balghusoon and S. Mahfoudh, "Routing protocols for wireless nanosensor networks and internet of nano things: A comprehensive survey," *IEEE Access*, vol. 8, pp. 200 724–200 748, 2020.

[21] F. Afsana, S. Mamun, M. Kaiser, and M. Ahmed, "Outage capacity analysis of cluster-based forwarding scheme for body area network using nano-electromagnetic communication," in *2015 2nd International Conference on Electrical Information and Communication Technologies (EICT)*. IEEE, 2015, pp. 383–388.

[22] F. Afsana, M. Asif-Ur-Rahman, M. R. Ahmed, M. Mahmud, and M. S. Kaiser, "An energy conserving routing scheme for wireless body sensor nanonetwork communication," *IEEE Access*, vol. 6, pp. 9186–9200, 2018.

[23] M. Pierobon, J. M. Jornet, N. Akkari, S. Almasri, and I. F. Akyildiz, "A routing framework for energy harvesting wireless nanosensor networks in the terahertz band," *Wireless networks*, vol. 20, no. 5, pp. 1169–1183, 2014.

[24] F. Büther, I. Traupe, and S. Ebers, "Hop count routing: a routing algorithm for resource constrained, identity-free medical nanonetworks," in *Proceedings of the 5th ACM International Conference on Nanoscale Computing and Communication*. ACM, 2018, p. 17.

[25] S. Canovas-Carrasco, A.-J. Garcia-Sanchez, and J. Garcia-Haro, "A nanoscale communication network scheme and energy model for a human hand scenario," *Nano communication networks*, vol. 15, pp. 17–27, 2018.

[26] A.-J. Garcia-Sanchez, R. Asorey-Cacheda, J. Garcia-Haro, and J.-L. Gomez-Tornero, "Dynamic multihop routing in terahertz flow-guided nanosensor networks: A reinforcement learning approach," *IEEE Sensors Journal*, vol. 23, no. 4, pp. 3408–3422, 2023.

[27] J. M. Jornet and I. F. Akyildiz, "Information capacity of pulse-based wireless nanosensor networks," in *2011 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*. IEEE, 2011, pp. 80–88.

[28] J. M. J and I. F. Akyildiz, "Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band," *IEEE Transactions on Nanotechnology*, vol. 11, no. 3, pp. 570–580, 2012.

[29] S. Mohrehkesh, "Energy harvesting-aware design for wireless nanonetworks," Ph.D. dissertation, Old Dominion University, 2015.

[30] G. Piro, L. Grieco, G. Boggia, and P. Camarda, "Simulating wireless nano sensor networks in the ns-3 platform," in *2013 27th International Conference on Advanced Information Networking and Applications Workshops*, 2013, pp. 67–74.